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Galileo Probe Doppler residuals as the wave-dynamical signature of weakly stable, downward-increasing stratification in Jupiter's deep wind layer

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Abstract. Doppler radio tracking of the Galileo probe-to-orbiter relay, previously analyzed for its *in situ* measure of Jupiter's zonal wind at the equatorial entry site, also shows a record of significant residual fluctuations apparently indicative of varying vertical motions. Regular oscillations over pressure depth in the residual Doppler measurements of roughly 1-8 Hz (increasing upward), as filtered over a 134 sec window, are most plausibly interpreted as gravity waves, and imply a weak, but downward increasing static stability within the 5 – 20 bar region of Jupiter's atmosphere. A matched extension to deeper levels of an independent inertial stability constraint from the measured vertical wind shear at 1 – 4 bars is roughly consistent with a static stability of ~ 0.5 K/km near the 20 bar level, as independently detected by the probe Atmospheric Structure Instrument.

Introduction

The density stratification of Jupiter's deep wind layer, as imposed by the vertical gradient of mean molecular weight and/or non-adiabatic departures in the temperature lapse rate, is key to understanding its atmospheric circulation and meteorology (*cf*. Gierasch and Conrath, 1993). Numerical models of Jovian equatorial waves, spots and vortices (e.g. Li and Read, 2000; Showman and Dowling, 2000; Williams, 1997) must assume a specified stratification at deep tropospheric levels, as in the form of an adopted vertical profile of the Brunt-Vaisala frequency or some equivalent measure of the static stability. If the deep atmosphere (below the 1 – 5 bar level) were to conform sufficiently to an adiabatic interior, the observed cloud-top winds might extend throughout the molecular hydrogen envelope (*e.g.* Ingersoll and Pollard, 1982). If, however, there are strong buoyancy contrasts within a vertically hydrostatic wind layer, the stratification could be of controlling importance to the configuration and strength of the zonal jets, possibly via the dynamical adjustment of the latitudinal distribution of the potential vorticity (*cf*. Allison, 2000). The effect of a deep stable layer on the interior adiabat also has important implications for Jupiter's evolutionary history and could be linked to the planet's interior water abundance.

Unfortunately, vertical lapse rates in temperature below the 1 bar level cannot be inferred from available remote sensing data with sufficient accuracy to characterize small but dynamically significant departures from an adiabatic profile. *In situ* measurements of temperature and pressure by the Galileo Probe Atmospheric Structure Instrument (ASI) suggest the presence of a weakly statically stable region, with a lapse rate that is sub-adiabatic by some ~ 0.2 – 0.5 K/km down to the 20 bar level (Seiff *et al*., 1998; Magalhaes *et al*., 2000). Although dynamically significant, the indicated values are not greatly in excess of the ASI noise limits. A comparably weak static stability at the 1 – 5 bar level is also implied, however, by the inertial stability constraint on the Richardson number (Ri) for the Probe Doppler measurement of a vertical wind shear $\partial U/\partial ln p \approx 52 m \bullet s^{-1}$ per scale height (Atkinson *et al*., 1998). Assuming $Ri = R \bullet H \bullet S/(\partial U/\partial ln p)^2 \approx 1.3$ or greater (*cf*. Allison *et al*., 1995), with a gas constant $R = 3600\ m^2 s^{-2} K^{-1}$ and a scale height $H \approx 36$ km at the 3 bar level, the implied (lower limiting) static stability $S \approx (\partial T/\partial z + R/c_p) \approx 0.03$ K/km. These are so far the only *in situ* constraints on the static stability of Jupiter's troposphere.

The diagnostic analysis of atmospheric waves has, however, afforded an indirect, "seismographic" characterization of the static stability at deeper levels where their forcing and/or resonant trapping is seated. In this sense Jupiter is fortuitously registered with several visual and thermal features showing apparent vertical/longitudinal wave-phase oscillations at a variety of scales. Allison (1990) interpreted large-scale oscillations in the equatorial stratospheric temperature profiles retrieved from Voyager radio data as vertically propagating Rossby waves leaking out of a tropospheric waveguide, speculatively associated with a deep stable region imposed by a super-solar water cloud (Gierasch and Conrath, 1985; Del Genio and McGrattan, 1990). Recently, Ortiz *et al*. (1998) have analyzed an extensive Earth-based patrol of infrared features in Jupiter's equatorial atmosphere implying essentially the same horizontal wave-phase speed, vertical structure and static stability for this region. Ingersoll and Kanamori (1995) obtained a similar result based on their gravity-wave interpretation of the expanding wavefronts apparent at the sites of the Shoemaker-Levy 9 impacts, assuming a statically stable waveguide of the form studied by Ingersoll *et al*. (1994), with a Brunt frequency times the scale height increasing as the pressure depth. The inference of a deep tropospheric stable layer from the SL9 wavefronts has been challenged by Walterscheid *et al*. (2000), who claim that time dependent numerical simulations of the response to the modeled comet impact within a variably stable, sponge-topped stratosphere reproduce the observed phase speeds with a strictly adiabatic lapse rate below the 1 bar level.

Measured residual oscillations in the Galileo probe Doppler measurement now appear to provide a third avenue to the detection of deep static stability in Jupiter's atmosphere, via their diagnostic analysis as vertically propagating waves. Although subject to interpretation, the method is inherently the most sensitive *in situ* indication of deep tropospheric stability structure.

Probe Doppler Residual Measurements

The Galileo probe radio frequency was sampled at a rate of 1.5 Hz (at a 2/3 s period) throughout its atmospheric descent.

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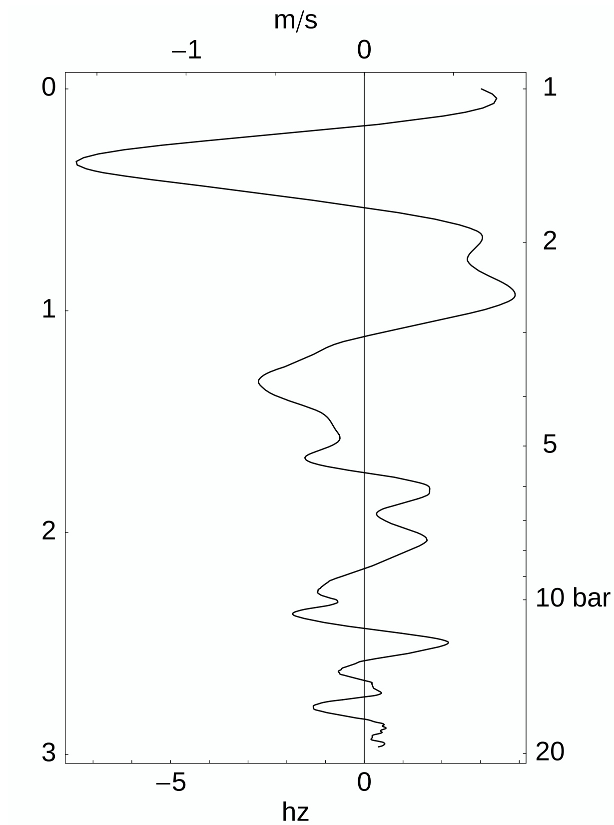

Figure 1. Filtered Doppler residuals in Hz plotted over log-pressure. The equivalent vertical velocity in m/s is indicated at the top. Pressure scale heights below the 1 bar level are marked on the left side ordinate, measuring $z^*=ln(1\text{bar}/p)$. The downward bunching and decreased amplitudes for the apparent oscillations below the ~ 4 bar level, interpreted as a vertically propagating waves, imply a downward increasing static stability.

Following the retrieval of the large scale zonal wind profile, the removal of the Doppler wind contributions from the frequency data yielded a vertical profile of remaining small residuals, as shown in Figure 7 of Atkinson *et al*. (1998). A number of short-period oscillations over roughly 10s periods are evident, and with peak-to-peak amplitudes up to about 12 Hz, presumably due to probe spin, pendulum motion, and possibly local aerodynamic buffeting and turbulence. As filtered by a simple 201-point averaging with a triangular weighting function, thereby removing the effects of the short period motions, the residual long period motions correspond to Doppler variations between 1 and 8 Hz, and are shown as plotted over even increments of log-pressure in Figure 1.

Based on the relationship between velocity and Doppler frequency ($\Delta\nu_{Dopp} = \nu_0 \Delta V/c$) where ν_0 is the frequency of the transmitted signal (1387 MHz) and c is the speed of light (3×10^8 m•s^{-1}), a one-meter per second variation in the probe to orbiter range rate results in a Doppler shift of about 4.6 Hz. Throughout the probe descent, the orbiter was almost directly above the probe (within -5 to +12 degrees) and variations in probe descent velocity were projected almost entirely along the line of sight. While it cannot be conclusively shown at this point that the inferred residual motions are entirely due to vertical velocity fluctuations, it seems unlikely that the oscillations apparent in the filtered signal for the continuously changing geometry of the probe relative to the orbiter are primarily the effect of variations in the meridional/zonal wind. Meridional wind variations between 8.3 and 12.4 m•s^{-1} would be required for a 1 Hz Doppler residual, as compared with variations in descent velocity of only 0.22 m•s^{-1}. The zonal velocity changes required for a 1 Hz Doppler residual varied between 2.5 m/s at the start of the descent, to infinity at orbiter overflight, to 0.9 m•s^{-1} at the end of the mission. The filtered residuals plotted in the figures account for the removal of the effects of the retrieved zonal winds.

Preflight testing showed that, following a 5-6 hour warmup, the probe ultrastable oscillator (USO) was stable to about 4 parts in 10^{10} over 30 minutes, corresponding to a frequency drift of approximately 0.5Hz in 30 minutes. During the cruise to Jupiter the USO was turned on and tested three times. In each case the measured 30 minute fractional frequency drift was somewhat higher, approximately 1 to 1.4 parts in 10^9 (corresponding to 30 minute frequency drifts of 1.387 to 1.942 Hz). But in all cases this drift was both uniform and monotonic and subsequently removed from the USO profile. As the probe descended through 10-12 bars, the internal temperatures surpassed the USO acceptance and qualification test limits of 50 and 60 degrees C, respectively, on the way to a final temperature of exceeding 140 degrees C. Post-flight thermal testing of three flight spare ultrastable oscillators characterized the USO behavior at temperatures and temperature rates measured on the probe at Jupiter. In each case the USO warmup profile and temperature cycling experienced during the post-flight tests showed the behaviors to be consistent and repeatable, leaving little doubt that the high temperature behavior has been characterized. The remaining uncertainty in the drift rate, less than 10^{-10}, corresponds to a residual frequency uncertainty over 30min of about 0.129 Hz. (*cf*. Table 1 in Atkinson *et al.*, 1998.)

The semi-regular oscillations, with upward increasing amplitudes, are most plausibly interpreted as the effect of a vertically propagating wave, although apparently not over even increments of altitude or log-pressure. As evident by the inspection of Fig. 1, the number of oscillatory inflections between 1 and 2 scale heights below the the 1 bar level, is only about half the number between 2 and 3 scale heights.

It is worth noting that the Galileo Probe signal was also tracked from the Earth, with a more favorable line-of-sight geometry for the zonal wind retrieval, as independently analyzed by Folkner *et al*. (1997). While the results provide a significant confirmation of the vertical shear of the zonal wind for the 1–4 bar region, the probe-Earth data do not extend to much deeper levels and lack the signal strength for the detection of vertical velocity variations as small as 0.5 m•s^{-1}.

Deep Tropospheric Structure and Wave Propagation

The vertical scale of a propagating wave depends upon the static stability via the *vertical structure equation.* In its “canonical” form,

$$d^2\chi/dz^{*2} + (\Gamma/gh - 1/4)^2\chi = 0 \qquad (1)$$

where $z^*= ln(p_0/p)$ is the log-pressure height coordinate, with p_0 the pressure at $z^* = 0$, and χ is a vertical structure variable proportional to $e^{-z^*/2}w^*$, where $w^* = dz^*/dt = w/H$, the vertical (log-p) velocity. [cf. eqns. 11 and A3 of Allison (1990) or 9.22 and 9.23 of Lindzen (1990).] $\Gamma \equiv N^2H^2 \equiv R(\partial T/\partial z^* + RT/cp)$ is the static stability parameter, $g = 23$m•s^{-2} the gravitational acceleration for Jupiter, and h the so-called “equivalent depth” for which the corresponding horizontal structure is the same as for a “shallow water” system of the same mean thickness. The equivalent depth parameter represents only one of several alternative and essentially equivalent characterizations of the vertical eigenvalue for a propagating wave, but affords the advantage of its immediate evaluation for the special case of a gravity mode in terms of the wave phase speed $(gh)^{1/2}$.

In a region of constant Γ, solutions to (1) are harmonic over height z^*, provided $0 < h < 4\Gamma/g$, and possess a vertical (log-pressure) wavelength $2\pi(\Gamma/gh - 1/4)^{-1/2} \leq 2\pi(gh/\Gamma)^{1/2}$. This appears to be a good representation of Jupiter’s equatorial stratosphere, where $\Gamma/g \approx 10$km (cf. Allison, 1990), and may

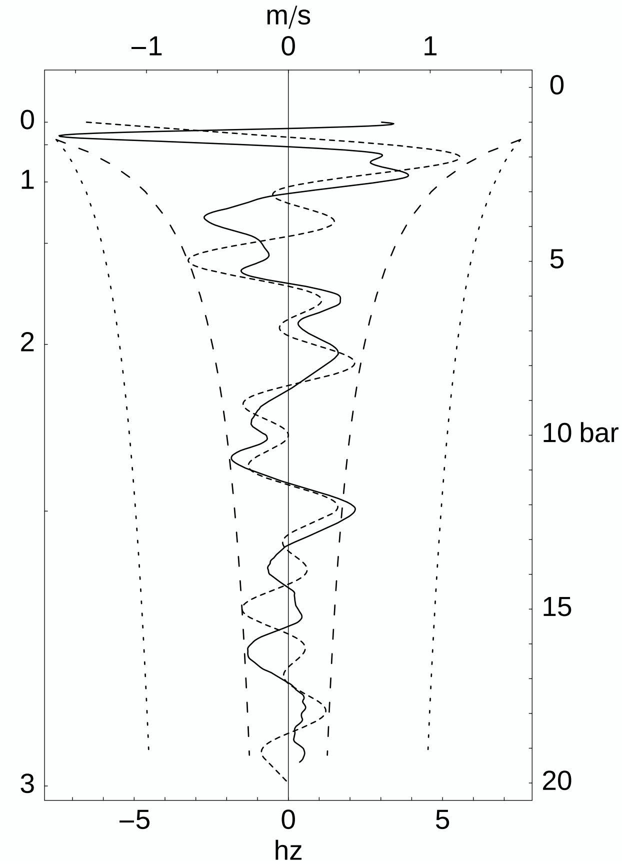

Figure 2. Filtered Galileo Doppler residuals (solid curve) and an idealized synthetic wave form (short dashed curve) plotted over even pressure increments. The upper spike in the filtered amplitude at the 1.4 bar level implies a vertical velocity of $-1.6\ m{\bullet}s^{-1}$. The synthetic, two-component wave corresponds to Eqn.(4), with $m_1 = 2\pi/5$bar, $m_2 = 2\pi/2$bar, $\phi_1 = 3\pi/2$, $\phi_2 = \pi/2$, and $W_1 = W_2 \approx 1\ m{\bullet}s^{-1}$. The funneled dashed curves represent model envelopes of the wave amplitudes.

also approximate the planet's upper troposphere, between 1 and 4 bar, where by the inertial stability estimate of the probe vertical wind shear $\Gamma/g = RHS/g \sim 0.2$ km. In such a region the wave vertical velocity $w = w^*H = H{\bullet}e^{z^*/2}\chi$. Then with $H \approx H_0(p/p_0)^{R/cp}$ the variable pressure scale height, and $R/c_p \approx 0.3$, w would be expected to vary approximately as $p^{-0.2}$.

But if at deeper levels $\Gamma(p) = \Gamma_0(p/p_0)^2$ or $NH = N_0H_0(p/p_0)$, as assumed by Ingersoll *et al.* (1994), solutions to (1) are instead of the form

$$w^* \equiv e^{z^*/2}\,\chi = (p_0/p)\ \Sigma_i W_i^*\ \mathrm{Sin}(m_i\ p + \phi_i) \qquad (2)$$

$$\text{where } m_i \equiv 2\pi/\lambda_i = (\Gamma_0/gh_i)^{1/2} p_0^{-1}. \qquad (3)$$

Here W_i^* represents the amplitude of dz^*/dt at the presure level p_0 and ϕ_i the phase for the ith wave component. Γ_0, N_0, and H_0 denote the (log-p) stability parameter, Brunt frequency, and scale height at the reference pressure p_0, referenced here to 1bar. A two-component solution to the vertical structure equation for such a region may be specified in terms of the vertical velocity $w = w^*H$ in meters per second, with (2) then transformed to

$$w \approx (1\mathrm{bar}/p)^{0.7}\ [W_1\mathrm{Sin}(m_1 p + \phi_1) + W_2\mathrm{Sin}(m_2 p + \phi_2)]. \quad (4)$$

As a ready visualization of the considered waves, Figure 2 shows the Doppler residual data plotted over linear pressure depth, apparently showing a more even spacing of the oscillations than for their log-pressure plot in Fig.1. For comparison, a simple harmonic waveform crudely indicative of the vertical structure of a two-component wave as described by (4) is also plotted as a dotted curve. The probe Doppler residuals below the 4 bar level appear to be crudely fitted with $m_1 \approx 2\pi/5$bar, $m_2 \approx 2\pi/2$bar, and W_1, $W_2 \approx 5$Hz($1m{\bullet}s^{-1}$/4.6Hz) $\approx 1\ m{\bullet}s^{-1}$, as assumed for the synthetic waveform. The funneled envelope indicated by the long dashed curves represents the sum of the amplitudes of the same two-component waveform, given as $(W_1 + W_2)(1\mathrm{bar}/p)^{0.7}$, while that for the short dashed curve shows the weaker modulation of a constant-stability region, proportional to $(1\mathrm{bar}/p)^{0.2}$. Again, the remarkably good fit to the data of the predicted envelope lends credence to the inferred downward increasing stability profile.

The fitted wavelengths are far too small to represent the trapped modes for the waveguide – corresponding to 1/4, 3/4, 5/4 etc cycles over the troposphere (cf. Ingersoll et al., 1994), themselves too large to be detected by the probe residuals, and therefore afford no direct numerical estimate of the Brunt frequency. But assuming that $NH = (RHS)^{1/2}$ can be continuously matched at the ~ 4 bar level to the inertial stability constraint for the Doppler-measured wind shear, as reviewed above, the static stability at deeper levels would be estimated as $NH = \Gamma^{1/2} \sim 60m{\bullet}s^{-1}(p/4\mathrm{bar}) = 15m{\bullet}s^{-1}(p/1\mathrm{bar})$ and $\Gamma = \Gamma_0(p/1\mathrm{bar})^2$, with $\Gamma_0 = 225m^2{\bullet}s^{-2}$. The vertical profile of NH would then be essentially the same as shown in Fig.2 of Allison (2000), though not necessarily extended to the same pressure depth. With $S = \Gamma/RH \sim 0.024\ K{\bullet}km^{-1}(p/1\ \mathrm{bar})^{1.7}$, the implied static stability as extended to the 22 bar depth of the Galileo probe link would be S(22 bar) ~ $0.5\ K{\bullet}km^{-1}$, the same as the deep value reported for ASI measurements by Seiff *et al.* (1998), equivalent NH ~ $300\ m{\bullet}s^{-1}$ at that level.

By Eqn. (3), $\lambda_{1,2} \approx 5$ and 2 bars would imply corresponding equivalent depths of $h_{1,2} = (\Gamma_0/g)(\lambda_{1,2}/2\pi p_0)^2 \sim 1$ and 6 meters and most plausibly correspond to gravity waves with phase speeds of $(gh)^{1/2} \sim 5$ and $12\ m{\bullet}s^{-1}$, since the (~1/3 smaller) phase speeds of the alternative Rossby modes would likely be too small to avoid their absorption by the weak vertical shear apparent in the Doppler data at the 5–20 bar levels (Atkinson *et al.*, 1998). Assuming h ~ 6 m ($<< 4\Gamma/g$) can be associated with the single oscillation over one scale height between the 1.5 and 4 bar levels apparent in Fig.1, this would be consistent with a roughly constant static stability there of $\Gamma/g \approx 4\pi^2 h \sim 0.2$ km, in good agreement with the inertial stability estimate from the probe wind shear. In the high (horizontal) wavenumber limit, the associated wave frequency is $\sigma = k(gh)^{1/2}$. Although the horizontal wavenumber k is not known, 1/H is a plausible upper bound consistent with hydrostatic motion (for which the vertical pressure scale must not exceed the horizontal scale), and slightly exceeds that for near-equatorial mesoscale features studied by Flasar and Gierasch (1986), with $k \approx 2\pi/300$ km. Then with h ~ 6m, and taking H(4bar) ~ 40km, the upper limiting estimate of the wave frequency would be $\sigma < 3 \times 10^{-4}\ s^{-1}$. From the thermodynamic equation, the amplitude of the associated thermal oscillations would be $\Delta T \sim S\ |w|/\sigma > 0.04 - 0.2$K, comparable to oscillations apparent in the ASI data (Magalhaes *et al.*, 2000).

Since the lower limiting time scale for wave variations, estimated as $\sigma^{-1} > 56$ min, barely exceeds the duration of the probe descent from 1 to 22 bars, it is possible that the apparent phase of the residual Doppler oscillations at the deepest measured levels is partly convolved with the temporal propagation, as well as the above noted small drift of the USO reference frequency (roughly 0.5 Hz over 30 min). The Doppler residual oscillations over apparently smaller pressure intervals between the upper 1–5 bar levels may reflect a more nearly uniform static stability there and may also be convolved with the effects of the Doppler measured wind shear. The consequent uncertainty in the precise wavelength, phase, and equivalent depth of the oscillations, does not, however, affect the inference of an overall downward increasing static stability for the deep wind layer.

Summary and Discussion

The vertical velocity oscillations indicated by the filtered Galileo Doppler residuals over roughly even increments of the pressure depth are plausibly interpreted as vertically propagating gravity waves and imply a weak but downward increasing static stability below the 5 bar level. Although the inferred wavelengths are too small to represent the trapped modes of the deep tropospheric waveguide, their apparent waveform provides the first *in situ* evidence within Jupiter's deep atmosphere of the static stability profile assumed by Ingersoll and Kanamori (1995), with NH (the Brunt frequency times the scale height) increasing roughly as the pressure depth. This qualitative corroboration lends confidence to the waveguide assessment of a deep-seated stable region based on independent but mutually consistent estimates of the equivalent depth of planetary-scale waves in Jupiter's equatorial region (Allison, 1990; Ortiz *et al*., 1998), with NH exceeding 300 $m \cdot s^{-1}$ in the deep wind layer. The downward increase of the static stability is also qualitatively consistent with various models for the large-scale stabilization of the Jupiter wind layer by moist-convection, including contributions from the vertical gradient of mean molecular weight (e.g. Achterberg and Ingersoll, 1989; Del Genio and McGrattan, 1990; Nakajima *et al*., 2000). Although radiative zones might also stabilize an interior layer of the planet, recent estimates of the relevant opacities suggest this is most likely to occur at kilobar levels (Guillot, 1999). While the measured subsolar depletion of water at the probe entry site (Niemann *et al*., 1998) remains a significant puzzle, recent modeling of the possible effects of an equatorially trapped Rossby wave on the "hot spot" region apparently traversed during the atmospheric descent (Friedson and Orton, 1999) may account for this as a locally anomalous region. Whatever its source, the accumulated evidence for a statically stable layer (or "thermocline") in Jupiter's deep troposphere demands the account of realistic models of its circulation and dynamics, with an associated Rossby deformation scale, $L_D = NH/\Omega \sim 2000$km, comparable to the spacing of the planet's jet streams.

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